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Thermodynamic modeling and sensitivity analysis of ejector in refrigeration system

Jiapeng Liu, Lei Wang *, Lei Jia *, Xinli Wang

School of Control Science and Engineering, Shandong University, Jinan 250061, China

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ABSTRACT

This paper focuses on the problems of thermodynamic modeling and sensitivity analysis of the ejector in refrigeration. Firstly, a new thermodynamic model is proposed based on the assumptions of constant pressure mixing and constant area mixing. The proposed model contains fewer parameters and simpler structure compared with the traditional ejector models. Later, the sensitivity analysis of the ejector is carried out based on the adjoint sensitivity method. Three different sensitivity coefficients are given to reveal the relation between design parameters and ejector performance. The result shows that geometric parameters have the most influences on the entrainment ratio of the ejector. For the ejector using R600a, the sensitivity coefficients of entrainment ratio to A_t and A_m are -2.43% and 2.40% respectively.

1. Introduction

The utilization of the renewable energy, such as solar energy [1], is a feasible way to decrease the consumed energy of the refrigeration system [2,3]. Among all the refrigeration system, the ejector refrigeration system is attractive due to its low temperature requirement for the heat source [4]. Theoretical analysis and experimental result show that the ejector refrigeration system has a great potential in the energy conservation and environmental protection [5,6].

The ejector, as a key device in the ejector refrigeration system, is used to create a low pressure region in the evaporator. Even though the structure of the ejector is relatively simple, the internal mechanism of the ejector is complex due to the complexity of the supersonic flow field [7]. Zhu and Jiang [8] investigated the relationship between the shock wave structure and the ejector performance by using the visual technology. The flow field in the mixing chamber is influenced by both geometrical parameters and operating conditions. An analytical model was proposed for the prediction of the first shock wave length. However, Zhu didn't give a calculate method for the total flow field inside the ejector. A simulation result proposed by Besagni and Inzoli [9] showed that an accurate description of the flow field can be obtained based on the CFD technology. It indicated that the $k-\omega$ sst turbulence model has a better ability to calculate the flow field than other turbulence models. Even though CFD method is a favorable tool to analyze the flow field of the ejector, it needs a relatively long calculation time and has a high requirement for the computing machine. Furthermore, the analysis and optimization of the total refrigeration system based on the CFD method are time consuming and difficult. Hence there are still many researchers working on the study about the thermodynamic modeling of the ejector [10].

In order to simplify the modeling procedure of the ejector, many assumptions, such as one dimensional flow, constant pressure mixing and constant area mixing, are made [11–13]. Huang et al. [14] proposed a double choking model to predict the performance of the ejector under the critical mode, and then Chen et al. [15] extended the model to the subcritical mode. By identifying the component efficiencies, Li et al. [16] further improved the accuracy of the model. However, the existing models still contain many parameters and couple equations, which make the analysis of the relation between design parameters and performance indicators difficult and complex. Hence the relations between the ejector performance and design parameters were indirectly investigated by analyzing the performance curves of the ejector in the past. The 3D graphics proposed by Bellos and Tzivanidis [17] showed that the optimum values of the primary flow temperature are from 387.15 K to 430.15 K for a solar ejector refrigeration system. Another 3D picture, which depicts the variation of exergetic efficiency, showed that the exergetic efficiency decreases with the rising of the condenser temperature. Khennich et al. [18] investigated the influence of irreversibilities on the ejector performance based on a real gas model. The change curve of the exergy destruction

* Corresponding authors.
E-mail addresses: leiwang@sdu.edu.cn (L. Wang), jialei@sdu.edu.cn (L. Jia).

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Nomenclature

$\dot{m}$	mass flow rate (kg/s)
A	area (m^2)
C_p	specific heat of gas at constant pressure ($J/(kg \cdot K)$)
D	diameter (m)
h	specific enthalpy (J/Kg)
M	Mach number
P	pressure (Pa)
P_d^*	critical back pressure (Bar)
R_g	gas constant ($J/(kg \cdot K)$)
T	temperature (K)
V	speed (m/s)

Greek letters

η	primary nozzle efficiency
γ	specific heat ratio of gas
ω	entrainment ratio
ϕ	mixing efficiency
ρ	density (kg/m^3)
φ	area ratio between real expansion area an ideal expansion area

Subscripts

$1, \ldots, 5$	cross section
c	outlet of the condenser
d	diffuser
e	outlet of the evaporator
ei	inlet of the evaporator
g	outlet of the generator
gi	inlet of the generator
m	mixing flow
p	primary flow
s	secondary flow
t	throat

showed that the exergy destruction decreases linearly with the rising of η_m.

Even though a great number of researches have been done on the relation between ejector performance and design parameters, they can't give an accurate value to distinguish the effects of the design parameters on the ejector performance. Quantization relations between design parameters and evaluating indicators are necessary to reveal the internal mechanism of the ejector. Wacholder et al. carried out a sensitivity analysis of the ejector by using the adjoint sensitivity method (ASM) [19]. The sensitivity coefficients, which are used to evaluate the influence of the design parameters on the ejector performance, can be obtained by matrix operations accurately. However, only the relationship between design parameters and the critical back pressure was discussed. Sensitivity coefficients of other indicators, such as the entrainment ratio, were not mentioned.

In this paper, a thermodynamic model is proposed for the sensitivity analysis of the ejector. The main contributions of the paper are: 1. A new mathematical model of the ejector is proposed based on the assumptions of the constant pressure mixing and constant area mixing. The proposed model has fewer parameters and simpler structure compared with the existing models [10]. 2. The sensitivity analysis is carried out based on the adjoint sensitivity method. The influences of design parameters on the entrainment ratio, critical back pressure and COP are discussed.

2. Background of the ejector refrigeration system

The typical structure of the ejector refrigeration system is shown in Fig. 1. Compared with the traditional vapor compression refrigeration system, a new fluid circuit, which contains an ejector, a generator and a pump, is used to recover the low grade energy. In the generator, the work fluid is evaporated by absorbing the heat of the low grade energy, and then the high pressure refrigerant is delivered to the ejector. Fig. 2(a) shows a principle structure of a typical ejector and Fig. 2(b) shows an ideal pressure distribution inside the ejector chamber. The primary flow expands inside a convergent-divergent nozzle. Hence the flow is choking at the cross section 1-1 and leaves the primary nozzle with a supersonic speed at the cross section 2-2. The supersonic flow creates a relatively low pressure region insider the ejector. Thus, the vapor in the evaporator is sucked into the ejector and mixed with the primary flow at the cross section 3-3. At the cross section 4-4, the primary and secondary flows are fully mixed. When the ejector works under the critical mode, the speed of the fully mixing flow is still larger than the sonic speed. Hence a final shock wave happens at the section 5-5, and the speed of the mixing flow drops to subsonic suddenly. The subsonic flow continues to compress in the diffuser chamber. In order to complete the fluid cycle, all the vapors are condensed in the condenser. Part of the liquid refrigerant is pumped into the generator with a high pressure. The other liquid become a very low pressure fluid by crossing the expansion valve and then is delivered to the evaporator.

The ejector is a key device that connects the refrigeration cycle and the power cycle. The performance of the ejector is evaluated by the entrainment ratio ω, which is defined below.

$$\omega = \frac{\dot{m}_s}{\dot{m}_p} \tag{1}$$

Meanwhile, the coefficient of performance of the total refrigeration system is defined by

$$COP \approx \omega \frac{h_e - h_{ei}}{h_g - h_{gi}} \tag{2}$$

In order to simplify the analysis procedure, it is assumed that both h_{ei} and h_{gi} are equal to h_c.

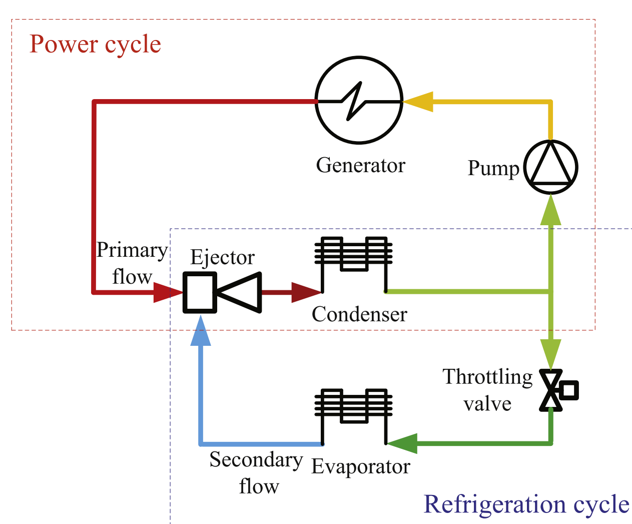

Fig. 1. Schematic of the ejector refrigeration system.